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(54) Control system for calibrating and driving ultrasonic transducer.

(57) An electronic control system for determining the resonant frequency of and driving ultrasonic transducers in a phacoemulsification probe used for ophthalmic surgery. The control system includes a voltage control led oscillator, power amplifier, power monitor, and automatic gain control circuit operating under the direction of command signals received from a microprocessor-based control console. The control system operates in a constant apparent power, direct drive mode with closed loop feedback maintaining the electrical power provided to the primary of a RLC transformer at the constant level requested by the command signals from the console. The frequency of the drive signal is held at the dominant resonant frequency of the ultrasonic transducer which is being driven by the control system. This resonant frequency is determined via a calibration procedure performed when the probe is first attached to the control system. During this procedure a constant voltage drive signal is swept through a range of frequencies and the electrical power consumed by the transducer is measured and stored at selected intervals such as 100 Hertz increments. The resonant frequency is also determined in part by looking for the frequency at which maximum power is consumed by the probe. The stored data is also subjected to other tests to cheok that the peak is indeed a resonant frequency and that the probe has selected output power characteristics about this resonant frequency thus helping to ensure that the probe is capable of operating satisfactorily when driven by the control system.

the range of 26.0 KHz to 32.0 KHz for the transuucers normally used with the Storz phaco probe shown in Figure 1. The present application will thus refer to a resonant frequency range between 26 KHz to 32 KHz, but those skilled in the art will appreciate the applicability of the present disclosure to ultrasonic transducers for medical instrument probes which operate at different frequencies.

One system for applying such driving signals to crystals 32 and 34 has been commercially used in the ophthalmic surgical console system from Storz which is sold under the trademark "DAISY."

Figure 2 presents a block diagram of the driving circuit 80 used in the DAISY console. As is well known, the piezoelectric transducer 22 may be modeled as an RLC series resonant network in parallel with a capacitance when operating under load and near the transducer's resonant frequency. (This model of the transducer is not shown in Figure 2.) Being a closed loop system, the driving circuit 80 is essentially an oscillator which fulfills the Barkhausen criteria for oscillation, namely it has zero phase shift and unity loop gain. The design frequency of the oscillator may be set at 28.5 KHz plus or minus 0.5 KHz for a transducer which has a nominal resonant frequency around 28.5 KHz. The feedback portion 84 of the closed loop includes an injection oscillator 88, a band pass active filter 90, low pass active filter 92, and a variable gain amplifier 94. The injection oscillator 88 provides an initial voltage signal at a frequency near the transducer resonant frequency to the injection control circuitry 96. That initial signal is disengaged from the loop of the feedback portion 84 by circuitry 96 once the driving circuit 80 provides a signal strong enough to maintain transducer oscillation. The band pass and low pass filters 90 and 92 provide the appropriate frequency selectivity and phase shafts characteristics to maintain the strength of the transducer feedback signal while the transducer phase characteristics vary over a normal operating range. The signal fed back on line 98 from the transducer 22 is derived over a compensation network 100 which provides additional frequency selectivity and phase shift stability. The variable gain amplifier 94 is used to establish the loop gain during initial calibration of the filter circuits 90 and 92, and thereafter remains fixed after the calibration is complete.

A power amplifier and transformer section 104 provides a maximum driving voltage of about 380 volts RMS with a maximum current of about 10 mA RMS. A gain control network 106 provides a stable voltage signal output by comparing the driving voltage on line 110 with a command voltage reference level on line 112 provided by a command signal derived from a control console in accordance with the power level desired by the surgeon using the phaco probe 20, and then compensating for any differences by adjusting the gain of the power amplifier of section 104.

In operation, the closed loop portion 84 of the driving circuit 80 attempts to compensate for changes in the resonant frequency of the transducer and/or phaco probe. This changing resonance is due to a variety of local factors which materially influence the ultrasonic transducer 22 and/or probe 20. Possible factors which can vary while the probe 20 is being used include the following: (1) the degree of compression of the transducer 22 on account of changing thermal or mechanical conditions; (2) the variations in the density or other properties in the fluid and/or debris being sucked by the vacuum through the channel 72 of probe 20; (3) the mechanical pressure brought to bear against the tip of the needle 28; (4) the quality of the coupling between the resonator 26 and needle 28; and (5) changes in the efficiency of the transmission of ultrasonic energy between the crystals 32 and 34 and the resonator 26 due to minute air gaps or mechanical deformations which may occur over time. One advantage of the driving circuit 80 of Figure 2 is that the closed loop section 84 continually attempts to make the frequency of the input signal applied to the probe 20 match the changing resonant frequency of the transducer 22 and probe 20 combination during use. Although the Q of the resonator 26 itself is very sharp, on the order of 1,000 to 2,000, and its bandwidth is very narrow, on the order of 15 to 30 Hz, the Q of the over-all probe/transducer combination is much less on the order of 40 to 100, which results in a much wider bandwidth, on the order of 300 to 750 Hz. Thus even with the closed loop system, it has proved difficult under actual conditions to achieve consistently the desired match up between the frequency of the input signal to section 104 and the actual instantaneous resonant frequency of the transducer/probe combination.

As is well known, it is beneficial, in terms of operating efficiency, to provide a driving signal to an ultrasonic transducer at its nominal resonant frequency. It has also been determined that when there is a slight mis-match between the frequency of the input signal and the natural resonant frequency of the transducer/probe combination, the stroke length of the needle is varied even as the command voltage supplied on line 112 from the console remains constant. At times, this mis-match of frequencies can result in a noticeable change in the ability of the oscillating needle 28 to perform its function, such as shattering the cataract within the eye. An operating surgeon who notices this change in performance will tend to compensate for such variations by either increasing or decreasing the strength of the command signal as needed. How-

invention, there is provided an electronic control system for determining the dominant resonant frequency of an ophthalmic surgical instrument containing an ultrasonic transducer and for thereafter driving the transducer at its dominant resonant frequency. This control system comprises: (a) means for producing a variable frequency alternating current ("Ac") electrical signal to power the ultrasonic transducer; (b) means for monitoring electrical power consumed by the transducer from the AC electrical signal at any frequency of interest within a given range of frequencies; (c) means for determining at which frequency within the range of frequencies is the dominant resonant frequency under test conditions; (d) means for automatically commanding means (a) to produce its AC electrical signal at the determined dominant resonant frequency and at a desired level of power specified by a desired power command signal; and (e) automatic closed loop feedback control means, responsive to the means for monitoring, for adjusting the power of the AC electrical signal produced by means (a), such that a substantially constant level of power is consumed by the ultrasonic transducer substantially independently of changing conditions experienced by the probe when the desired level of power remains constant.

According to a fifth aspect of the present invention, there is provided an apparatus for automatically determining the resonant frequency of an ultrasonic transducer along the lines outlined in the first aspect of the present invention above.

According to a sixth aspect of the present invention, there is provided an apparatus for driving an ultrasonic transducer of an ophthalmic surgical instrument by regulating the electrical input power provided to the instrument. The apparatus comprises: (a) means for producing a first low power electrical signal having a first characteristic proportional to a desired power level; (b) means, adjustable under control of at least one feedback error signal, for amplifying the first low power electrical signal to produce a higher power electrical signal oscillating at a selected ultrasonic frequency; and (c) automatic closed loop feedback control means for producing at least one feedback error signal to adjust the level of amplification of the means for amplifying such that a substantially constant level of power is consumed when the desired power level remains constant.

The conceptual basis for the present invention is the belief that the electrical power consumption of an acoustic resonant transducer operating in a fundamental vibration mode is directly correlated to the vibration amplitude of the transducer. From a practical view point, a given population of acoustic transducers will have differing resonant frequencies and impedances. Therefore, one goal of the methods and control system of the present invention is to level out the performance of these transducers devices as measured by vibration amplitude. Since the acoustic resonator, for example the type shown in Figure 1, may be used to mechanically drive a hollow phaco needle, the excursion of the needle tip, that is the cyclical stroke length, may be used to measure the performance of the entire phaco probe.

Previous phacoemulsification probe drive systems have used a variety of constant voltage or constant current circuit schemes. For example, the Figure 2 phaco drive circuit described above used a constant voltage oscillator structure, where the availability of a drive signal depends directly on the compatibility between the probe's impedance characteristics and the probe's electrical interactions with both the amplifier output circuit and the feedback network. Accordingly, it is necessary to match the characteristics of the probe to be driven quite closely to the characteristics of the amplifier output circuit and feedback network.

In contrast the phaco drive system of the present invention operates in a constant power, direct drive mode. There is always a drive signal available. Further, the frequency of this drive signal is fixed based upon results of successfully completing a calibration routine. This routine or method is designed to find the fundamental resonant frequency of the phaco probe, and to ensure the compatibility between the probe power spectral characteristics and the driving circuit of the present invention.

These and other objects, advantages and aspects of the methods and drive system of the present invention may be further understood by referring to the detailed description, accompanying figures and dependent claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The drawings form an integral part of the description of the preferred embodiments and are to be read in conjunction therewith. Like reference numerals designate the same or similar components or features in the various Figures, where:

Figures 1A and 1B show, in longitudinal cross-section and in exploded perspective view respectively, a prior art phacoemulsification probe including an ultrasonic transducer used in ophthalmic surgical procedures;

Figure 2 is a block diagram of a prior art electronic control system for driving an ultrasonic transducer used in ophthalmic surgical procedures;

Figure 3 is a simplified block diagram of the

The block diagram of the Figure 3 control system 120 shows two distinct control loops. Th outer loop begins and ends with the microcomputer 122 and includes sections 136, 138 and 142. This loop is active only during the phaco calibration procedure which will be described in greater detail later, but may briefly be described now as follows.

The processor 124 sends a series of signals representing different frequency commands to the VCO section 134, where the commands are each converted to a voltage level representing the desired frequency. A sine wave signal V_U is output by VCO section 134 on line 154, and is amplified by amplifier section 136, and presented via line 156 to the transformer section 142 which applies it to the phaco handpiece 20. The error correction command signal on line 160 applied to the power amplifier section 136 is a fixed value on account of the control signal on path 163 to the AGC section 140 by the processor 124. The power monitor 138 samples the voltages being applied to the transformer/probe via line 170 and also samples the current returning from the transformer section 142 via line 172. From these samples, the electrical power is computed in power monitor section 138, and an analog voltage signal (M_P) having an amplitude corresponding to the monitored power level is produced and output by section 138 on line 168.

The value of this analog voltage M_P is also delivered to the microcomputer 122, via ADC 175 which converts it to 12 bit digital data and transmits it back to the processor 122 as the "load power" value, that is the electrical power consumed by the probe 20. The processor 124 fills a table in memory 125 with ordered pairs consisting of signal frequencies and load power information. Several tests are performed on this data, which will be described later below, which ensure a minimum compliance of the curve representing the acquired data against standard curve for an ideal ultrasonic transducer/probe combination. Certain variances from the standard curve indicate specific types of failure conditions existing in the phaco handpiece 20, such as open or short circuits, missing or loose needles, and excessively damped transducers. These tests will also fail of the wrong transducer type is connected to the transformer section 142.

If the initial calibration procedure is successful, the processor 124 will store the frequency at which the load power was at a maximum. That single frequency will then be used when driving the phaco handpiece 20 until such time as the next phaco calibration sequence is performed. After calibration, the outer control loop just described is opened, and the inner control loop is engaged.

The inner control loop uses the automatic gain control section 140 as well as sections 136, 138 and 142. When the inner control loop is to be engaged, an appropriate control signal is provided on path 163, which enables an automatically determined error correction signal on line 160 to be provided to the power amplifier section 136.

The operation of the automatic gain control section 140 may be summarized as follows. When the processor 124 commands a specific percent power level via signal C_{P2} on path 162, an analog reference voltage is generated internally with the ACG section 140. The voltage representing load power on line 168 is compared to this reference voltage and the difference is integrated in the hardware of the AGC section 140. The output of an internal integrator circuit is provided as the error correction signal E_C on line 160, and drives the gate of a field effect transistor ("FET") located in power amplifier section 136. The channel resistance of this FET provides a shunt path to ground for the desired power level command signal V_U provided on line 154. The larger the channel resistance of the FET, the stronger the power signal provided to drive the probe 20. The result of the operation of the closed loop is that the amplitude of the power signal on line 156 is constantly changing to match the changing impedance characteristics of the probe 20.

Figure 4 shows a detailed block diagram of the control system 120 shown in Figure 3, except for the microcomputer system 122. In particular, Figure 4 shows all of the functional hardware components which constitute part of the driving circuitry of control system 120. The major blocks shown in Figure 3 are shown in dashed lines in Figure 4 to facilitate comparison between Figures 3 and 4. The components within the various blocks will be discussed, followed by an explanation of the interaction of the various sections.

VCO section 134 includes a digital-to-analog converter ("DAC") 210, a voltage controlled oscillator 212, pre-amplifier 214, a frequency counter 216 including a digital counter section 218 and control interface 220 and a second DAC 222. The first DAC 210 receives the frequency command signal on path 152 in digital form and converts it to a corresponding analog voltage on line 226 which inputs it into the oscillator 212. VCO 212 produces a sinusoidal output signal having a frequency corresponding to the applied input voltage. The design of the voltage controlled oscillator 212 is conventional, and may be designed to produce an output signal in a selected range of frequencies. In the preferred embodiment, the VCO 212 produces 35 kilohertz at the minimum input voltage and 21 kilohertz at the maximum input voltage V_{CC}. DAC 210 and DAC 222 preferably have 12-bit resolution for 4,096 different possible output values. Pre-amplifier 214 strengthens and smoothes out the sinusoidal signal on line 228 to produce a fixed

king the output signal on line 344 from passing to line 160. In its other state, the control signal on line 342 causes analog switch 340 to be fully conducting, thus allowing the output signal of line 344 to pass freely to line 160. Those in the art will appreciate when analog switch 340 is rendered nonconducting by the signal on line 342, the AGC section 140 is effectively removed from the control system, as was described within the explanation of the calibration procedures above with respect to Figure 3.

DAC 332 converts the digital C_{P2} on path 163 to an analog value V_{C2} on line 352. Signal V_{C2} is multiplied by G in amplifier 334 and passed to both inputs of multiplier 336. The resulting output signal on line 356 of multiplier 336 is thus proportional to the square of the input signal presented in line 354. The motivation for using the multiplier 336 in the AGC section 140 is that it effectively increases the dynamic range of AGC section 140 which not sacrificing much if anything in the way of accuracy. In the preferred embodiment, the digital value C_{P2} is proportional to the square root of the desired power level signal C_{P1}, whose value is proportional to desired level of power communicated by the surgeon to the microcomputer 122. If multiplier 336 were not used, then the signal C_{P2} would be directly proportional to the desired level of power and the output of scaling amplifier 334 would be fed directly to the positive input of integrating difference amplifier 338. By providing the square root of the desired power signal as the digital value C_{P2} on path 162, the AGC section is provided with greater sensitivity at lower values of desired power, which can be advantageous from a user's point of view.

Difference amplifier 338 includes a feedback capacitor 358 so that AGC circuit thus employs both proportional and integral, while still providing feedback control. As is well known, integral feedback control has the beneficial tendency under steady-state loop conditions to drive the absolute errors in closed loop feedback system to zero. In the preferred embodiment, the capacitor 358 is sized to have an RC time constant of approximately 35 to 100 milliseconds with about 50 to 65 milliseconds being preferred, and the amplifier 338 preferably has a gain of about one.

When the inner loop is engaged, the control system 120 shown in Figure 4 continuously provides a driving signal V_A on line 156 whenever the desired power level signals C_{P1} and C_{P2} are non zero. Further, the frequency of the driving signal when the probe 20 is in use is always set at the dominant resonant frequency of the transducer/probe combination, as determined by the calibration procedure, which will be more fully explained shortly. The effect of changes in the actual instantaneous resonant frequency of the combination of the probe 20 and its ultrasonic transducer 22 is compensated for by the error signal E_C produced by the AGC section 140, which automatically adjusts the effective gain of power amplifier section 136 as needed. As can be seen from the foregoing discussion of power monitor section 136 and AGC section 140, the actual electrical power consumed by the probe/transducer combination is compared against the desired power level to obtain the correction signal. For stability and in order to eliminate long-term offset errors in the closed loop system, difference amplifier 338 integrates the error signal on its output 344.

Those in the art should appreciate that the hardware shown in Figure 4 does not monitor or otherwise take into account the relative phase differences which may exist between the phases of voltage signal V_A and current signal I_L. Thus, the Figure 4 embodiment actually monitors apparent electrical power consumed by the probe/transducer combination, rather than true (or real) electrical power consumed. However, in the aggregate, the phase differences are usually small enough to be insignificant, and therefore may be safely ignored, or are relatively constant over the range of changing resonant frequencies for any given probe, and thus are also transparent to the user of the control system 120. Thus, the preferred embodiment of the present invention does not monitor this phase difference. However those skilled in the art will appreciate that, if desired, the true electrical power consumed by the probe/transducer combination could be monitored by providing an additional circuit to take into account the difference between apparent power and actual power resulting from phase shifts between signals V_A and I_L.

Figure 4 also shows a power relay 360 having a coil 362, normally closed contact 364 and normally open contact 366. The relay coil is energized when a signal interface circuit 368 receives a control signal 370 from microcomputer 122 directing that the relay be turned on. When coil 362 is de-energized, normally closed contact 364 is closed, thus allowing the signal on line 156 to pass through to line 156a and onto transformer section 142. When coil 362 is energized, normally closed contact 364 opens, and normally open contact 366 closes, which directs the power of amplifier 240 from the signal on line 156 to a 60 watt load resistor bank 374 connected to ground. The use of relay 360 and dummy load resistance 374 allows the microcomputer 122 to verify that the circuitry in Figure 4 is operating properly. In particular, before surgical use of the control system 120, microcomputer 122 can verify a proper operation of the control system 120 by energizing relay 362 and applying known power command signals to the

ducers is of no major concern. In order to have both families of transducers being successfully driven by the electronic control system of the present invention, then only the power amplifier selection and frequency band widths of the various sections of the control system need be selected and designed to operate over the desired range of frequencies. As may be seen from Figure 5, the power amplifier section 136 is easily made to operate over a primary impedance range of 2.2 ohms through 10.4 ohms by simply limiting the maximum power produced by amplifier section 136 to an appropriate fraction of its peak power, such as about 35 percent as shown in Figure 5.

In prior art driving systems for phaco probes, the difference un peak electrical power consumption between transducers populations is a major concern, particularly for drive systems employing a constant voltage strategy. In fact, the graphs in Figure 6 were generated from a nearly constant voltage drive source. The input voltage to the power amplifier driving the RLC transformer section was constant, but there was no compensation circuitry to maintain the output voltage constant. So as the load impedance varied, so did the output voltage of the power amplifier because of the voltage divider relationship between the load impedance and source (output) impedance. This relationship is largely responsible for the power transfer characteristics shown in Figure 6.

Figure 7 demonstrates the similarities between transducer performance of the two populations of transducers shown in Figure 6 when driven by the phaco drive system of the present invention shown in Figure 4. Since the effective impedance of the two transducer populations, namely 4.2 kilo-ohms and 8.4 kilo-ohms, are within the constant power drive range of the power amplifier section 136 and step-up transformer sections, (which range extends from about 2 kilo-ohms to about 9.3 kilo-ohms), there is no problem with maintaining constant power at the output of the transformer secondary. Thus, as shown in Figure 7, the performance of probe 20 using a transducer 22 from either family is remarkably similar.

Another advantage of the present invention is that, even of the impedance characteristics of the transducer/probe drift outside of the constant power amplifier range, so that constant power cannot be strictly maintained, the drive system of the present invention will nevertheless strive to deliver a proper amount of power to the transducer. This is far superior to the total loss of power experienced with some phaco drive systems under such conditions.

The Figure 7 graph shows the close correlation between the results achieved by the electronic control system 120 of the present invention when driving the two different families of transducers shown in Figure 6. Dashed line 420 represents the actual stoke length (in mils) as a function of percent power command for those transducers having a nominal impedance of 8.4 kilo-ohms. Solid curve 422 represents the performance of those transducers having a nominal impedance of 4.2 kilo-ohms when driven by the control system of the present invention. As Figure 7 graphically shows, the resulting performance of phaco probes using either type of transducer is nearly identical. The performance is also quite linear over the range from 10% power to 100% power. The slight nonlinearities in the curves 420 and 422 are believed due to saturation effects in the ultrasonic transducer due to power limitations. However, as a practical matter, these nonlinearities should be inconsequential to ophthalmic surgeons, since the surgeons are interested principally in consistency, repeatability and reasonable (not perfect) linearity, all of which characteristics are achieved by the drive system of the present invention.

Figure 8 shows a prototypical or standard curve of consumed power versus drive frequency of an ultrasonic transducer having a true or dominant resonant frequency of about 30 kilohertz. The shape of the curve is also representative of the consumed power curve for other ultrasonic transducers used in phaco probes which operate at different frequencies. In other words, if the power consumed curve for an ultrasonic transducer/probe combination (when assembled) resembles this curve within certain limits under known test conditions, then such evidence constitutes good proof that the tested transducer/probe combination is in proper operating condition and ready to be satisfactorily used by an ophthalmic surgeon. The determination of the resonant frequency of a given ultrasonic transducer/probe combination and the verification of proper operation of such combination constitutes two important and distinct aspects of the present invention. These aspects of the present invention are more fully explained below.

In order to simplify the following explanation, it is assumed that the range of normal frequencies of the transducers to be operated be the electronic drive system of the present invention conform to the families of curves shown in Figure 6. Further, the power amplifier section characteristics are assumed to be as shown in Figure 5.

The electrical power consumed by the transducer/probe combination to be test is determined by monitoring the voltage applied to and current passing through the primary 270 of the RLC transformer section 142 (Figure 3). The frequency at which peak power is consumed may be considered to be the dominant resonant frequency F_{DR} for the transducer/probe under test. The calibration procedure tests the transducer/probe by

again, this time from F_{AR} minus 200 Hz through F_{AR} plus 200 Hz at 5 Hz increments. This is done to determine more accurately F_{DR}, which is assumed to be the frequency at which the highest power consumed reading occurs during this fine sweep. Thereafter the transducer/probe combination is deemed ready to be used in surgical procedures and a message that had earlier been displayed upon the monitor 182 of the control console, such as "phaco calibration required", is cleared from the monitor. The control system 120 will then always drive that transducer/probe combination at the last F_{DR} determined during the calibration procedure.

The VCO 212 is preferably operated in an open loop fashion, since it is not necessary to operate it in a closed loop fashion. In other words, when the processor 124 commands VCO section 134 to operate at a specific frequency, say 28.3 KHz, it does not check the frequency counter to determine that the reading is actually achieved. Instead, it is assumed that the DAC 210 converter and the VCO 212 do not drift during the short time that the ultrasonic transducer/probe is being used. Note that even if the frequency output by the VCO is off by several Hertz, this will not matter since the key is not that the value of F_{DR} be known with great accuracy, but instead the frequency at which maximum power is consumed by the probe is used to drive the phaco probe under normal operating conditions. Also, the closed-loop feedback control system greatly stabilizes the consistency of the performance of the probe as a function of a stroke length versus applied power command, which is really what the ophthalmic surgeon is truly interested in.

The foregoing detailed description shows that the preferred embodiments of the present invention are well suited to fulfill the objects above-stated. It is recognized that those in the art may make various modifications or additions to the preferred embodiments chosen to illustrate the present invention without departing from the spirit and proper scope of the present invention. For example, transducers having significantly lower or higher resonant frequencies may be utilized, and the control system may be implemented more completely in hard-wired electronic circuits or more completely in digital circuits which minimize the use of analog signals by providing greater software control. Accordingly, it is to be understood that the protection sought and to be afforded hereby should be deemed to extend to the subject matter defined by the appended claims, including all fair equivalents thereof.

Claims

1. A method for driving an ultrasonic transducer of a ophthalmic surgical instrument at its dominant resonant frequency by holding the electrical power consumed by the transducer substantially constant at a desired level of power consumption by use of closed loop feedback control, comprising:

(a) generating an electrical signal oscillating at a desired ultrasonic frequency;

(b) amplifying the oscillating electrical signal;

(c) applying the amplified electrical signal to an ultrasonic transducer;

(d) monitoring how much electrical power of the amplified electrical signal is consumed by the ultrasonic transducer;

(e) comparing how much electrical power of the amplified electrical signal is being consumed against the desired level of power consumption; and

(f) automatically adjusting the power level of amplified signal to maintain the consumed electrical power substantially equal to the desired power level.

2. A method of claim 1 for automatically determining the resonant frequency of a surgical instrument powered by an ultrasonic transducer, comprising the steps of;

(a) providing an alternating current electric driving signal having a substantially constant voltage level to drive the ultrasonic transducer at any desired one of a number of frequencies within a given range of frequencies;

(b) monitoring the electrical power consumed by the probe at different frequencies within the range of frequencies;

(c) selecting an apparent resonant frequency within the range of frequencies by determining which frequency, out of those frequencies which were monitored, had the greatest electrical power from the driving signal consumed by the probe;

(d) comparing the amount of power consumed at the apparent resonant frequency with amounts of power consumed by the probe at a first frequency below the apparent resonant frequency, and at a second frequency above the apparent resonant frequency; and

(e) deciding whether the apparent resonant frequency is the dominant resonant frequency of the probe at least in part based upon the results of the comparisons performed in step (d).

3. A method as in claim 2 further comprising the step of:

(f) sweeping the driving signal through at least the given range of frequencies during step (b).

4. A method as in claim 2 wherein:

step (d) further includes comparing the amount of power consumed at the apparent resonant frequency with amounts of power consumed by the probe

FIG. 1A
PRIOR ART

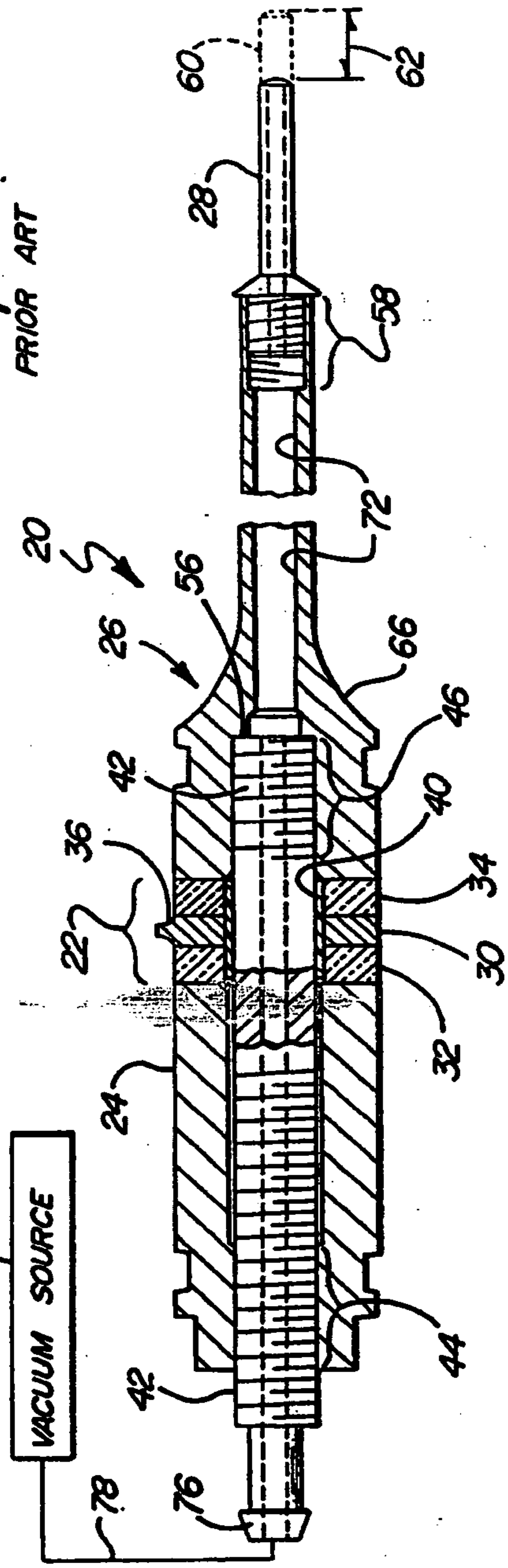
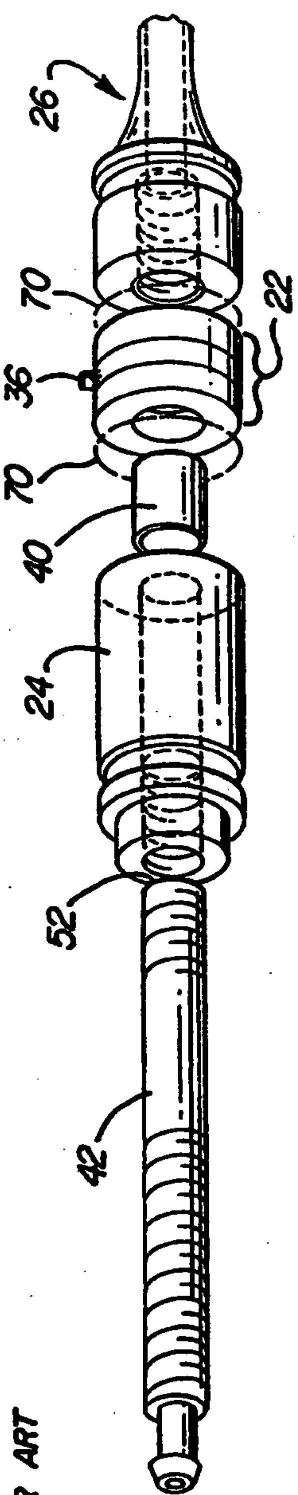
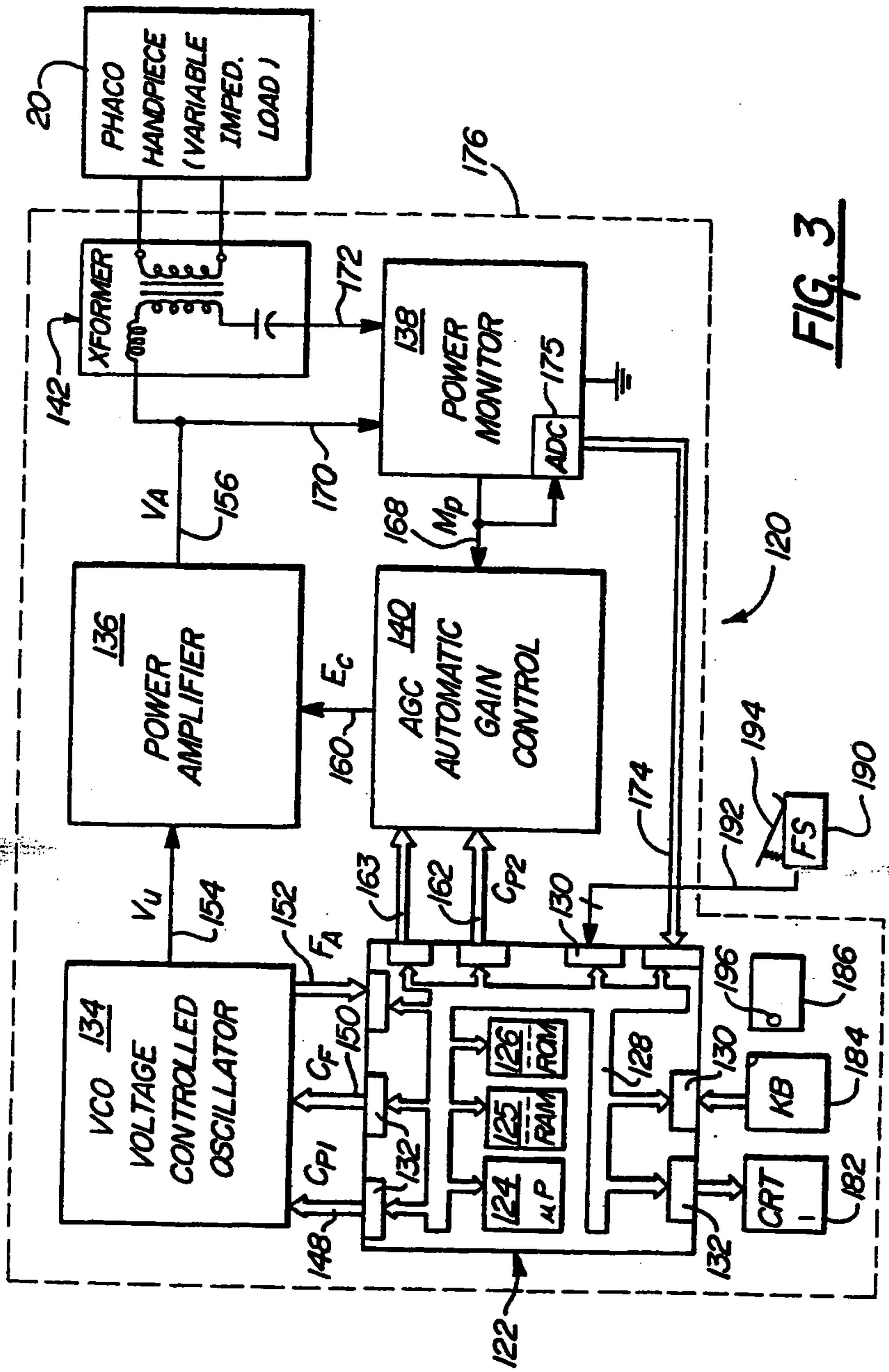


FIG. 1B
PRIOR ART





PHACO HANDPIECE (VARIABLE IMPED. LOAD)
20
176
XFORMER
142
172
138 POWER MONITOR
175
ADC
170
VA
156
136 POWER AMPLIFIER
168
MP
AGC 140 AUTOMATIC GAIN CONTROL
EC
160
120
VCO 134 VOLTAGE CONTROLLED OSCILLATOR
VU
154
FA
152
163
162
CP2
130
174
192
194
FS
190
CF
150
CP1
148
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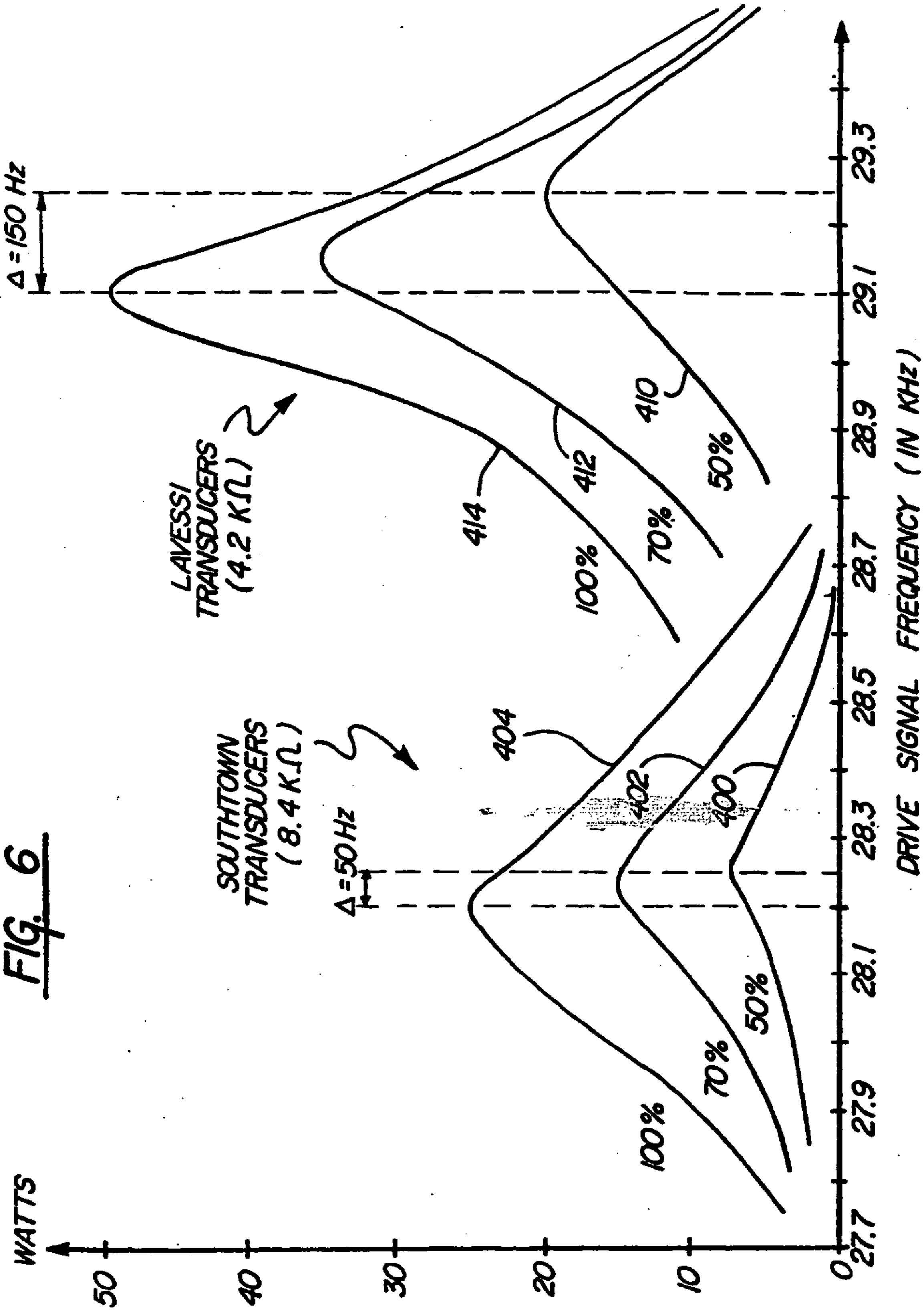
124 µP
125 RAM
126 ROM
128
196
186
KB
184
CRT
182
122

FIG. 3

FIG. 6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40
30
20
10
0
27.7
27.9
28.1
28.3
28.5
28.7
28.9
29.1
29.3
DRIVE SIGNAL FREQUENCY (IN KHz)
SOUTHTOWN TRANSDUCERS (8.4 KΩ)
LAVESSI TRANSDUCERS (4.2 KΩ)
Δ = 50 Hz
Δ = 150 Hz
100%
70%
50%
404
402
400
414
412
410

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(54) Control system for calibrating and driving ultrasonic transducer.

(57) An electronic control system for determining the resonant frequency of and driving ultrasonic transducers in a phacoemulsification probe used for ophthalmic surgery. The control system includes a voltage control led oscillator, power amplifier, power monitor, and automatic gain control circuit operating under the direction of command signals received from a microprocessor-based control console. The control system operates in a constant apparent power, direct drive mode with closed loop feedback maintaining the electrical power provided to the primary of a RLC transformer at the constant level requested by the command signals from the console. The frequency of the drive signal is held at the dominant resonant frequency of the ultrasonic transducer which is being driven by the control system. This resonant frequency is determined via a calibration procedure performed when the probe is first attached to the control system. During this procedure a constant voltage drive signal is swept through a range of frequencies and the electrical power consumed by the transducer is measured and stored at selected intervals such as 100 Hertz increments. The resonant frequency is also determined in part by looking for the frequency at which maximum power is consumed by the probe. The stored data is also subjected to other tests to cheok that the peak is indeed a resonant frequency and that the probe has selected output power characteristics about this resonant frequency thus helping to ensure that the probe is capable of operating satisfactorily when driven by the control system.

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